1415 N CHERRY AVE
CHICAGO, IL 60642
(312) 281-6900
DMDII.ORG
DMDII@UILABS.ORG

DMDII
a UI LABS Collaboration
DIGITIZING AMERICAN MANUFACTURING

DMDII FINAL PROJECT REPORT

Tolerance Analysis Tools and Techniques	
Principle Investigator / Email Address	Dr. Andreas Vlahinos / andreas@ae.nu
Project Team Lead	Advanced Engineering Solutions
Project Designation	15-11-01
UI LABS Contract Number	0320170006
Project Participants	Advanced Engineering Solutions and Sigmetrix LLC
DMDII Funding Value	$290,126.35
Project Team Cost Share	$741,894.00
Award Date	June 12, 2017
Completion Date	February 20, 2019

SPONSORSHIP DISCLAIMER STATEMENT: This project was completed under the Cooperative Agreement W31P4Q-14-2-0001, between U.S. Army - Army Contracting Command - Redstone and UI LABS on behalf of the Digital Manufacturing and Design Innovation Institute. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Department of the Army.

TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

Most engineering analyses performed today predict the performance of the product during use. Tolerance analyses, on the other hand, in addition to predicting the compliance to functional assembly criteria, predict how well the assemblies will perform while being built. When done properly such analyses will reduce the production costs of a design before the first chip is cut or first plastic injected into a mold. All too often, though, companies cite that they don't have as much coverage as they would like to have. Informal surveys of companies seeking tolerance analysis solutions indicate:

- 81% seek to reduce manufacturing problems caused by tolerance issues
- 43% seek to reduce the number of prototypes required and/or the duration of the prototype phase
- 38% seek to reduce field-service (i.e. warranty) issues caused by tolerance analysis issues.

One other key characteristic is that 76% want a tool that has better integration with the data in their CAD models. Unfortunately, while there are a few tools on the market capable of reading and updating PMI data in specific CAD systems, there is currently no single tool on the market that has the capability to read and update tolerance information across multiple CAD systems.

Sigmetrix LLC has focused on the development of a 1D tolerance analysis tool capable of defining tolerance studies on models generated in any CAD system.

There are several software tools that perform tolerance analyses of rigid assemblies. There are also several software tools that perform finite element analyses in order to determine deformations on flexible components. There is not a commercially available tool that can perform tolerance analysis on flexible components within the CAD environment. This research effort has filled that gap by coupling tolerance analysis and FEA tools. This capability will provide manufacturers with techniques to perform tolerance analyses of flexible assemblies and save millions of dollars every year on product quality issues.

Advanced Engineering Solutions has focused on the development of techniques for tolerance analyses of flexible assemblies.

II. PROJECT REVIEW

a. Project Scope and Objectives for the 1D tolerance analysis tool

With the support of DMDII Sigmetrix developed EZtol software. EZtol is a 1-Dimensional tolerance stack-up analysis program designed to assist in understanding the impact of the accumulation of part-level dimensional variation and part-to-part assembly variation sources and the impact that they have on assembly-level requirements.

Today such analyses are performed in a spreadsheet, most commonly Microsoft® Excel®. Much work is required in creating spreadsheets that manage all of the product requirements simultaneously with consideration of common dimensions and tolerances that feed each one, properly including the impacts of the more complex geometric tolerances, and properly calculating the statistical results. Analysis spreadsheets often include a visual diagram either from the model or an assembly-level drawing to help explain the components of each of the analyses, but these too must be maintained as updates are made.

Oftentimes all the work creating these spreadsheets doesn't reveal the full story because a 1-dimensional stack-up analysis may under-predict the actual assembly-level variation. EZtol helps you see the full story. The software warns if the tolerance stack-up is not 1D in nature with a note that the results provided may underestimate the actual variation that will occur during production.

The main software highlights are:

- Builds the analysis on top of the 3D design model:
  - Uses the actual nominal distances between surfaces/features from the design
  - Helps to ensure all components in the loop are included
  - Shows the optimum dimensioning scheme for the single analysis
- Automatically calculates the worst-case, RSS, and statistical results of the analysis. Metrics for statistical results can be reported as: Cpk, Sigma, DPMO, or % Yield.
- Lists of contributors sorted from largest to smallest.
- Define multiple tolerance stack-up analyses on the same model.
- Provides a summary table showing the objectives and results of each stack-up analysis along with a visual indication of whether the requirement has been met.
- Stores the dimensions, with tolerances, defined for each part so that the user doesn't have to re-enter them for each loop. This also allows the automatic updating of all analyses when the user makes a modification to a tolerance used in multiple analyses.
- Generates detailed report with graphical view of the dimension loop over the models involved and a graphical presentation of results and the top contributors.
- Provides an indication that the tolerance stack-up may not be 1D in nature including a note that the results provided may underestimate the actual variation that will occur during production.
- Doesn't utilize CAD license to work with CAD models.
- Works with files from most major CAD systems!

b. Project Scope and Objectives for Tolerance Analyses of Flexible Assemblies

Manufacturers spend millions of dollars every year on product quality issues such as parts not fitting together properly, scrap, and rework. Variation causes a large percentage of expensive and time consuming build problems and engineering changes.

Tolerance variation in rigid body assemblies results from three sources: size, form and kinematics. Size variation is derived from inconsistent dimensional lengths. Form variation is derived from geometric differences such as flatness or cylindricity. Kinematic variation is produced by small adjustments between mating parts in response to dimensional and geometric irregularities. Tolerance analysis software solutions such as CETOL from Sigmetrix, VisVSA from Siemens PLM and 3DCS from Dassault Systems are effective for rigid body assemblies and are fully integrated within the major CAD tools such as PTC/CREO, NX and CATIA respectively.

Flexible body assemblies exhibit an additional source of variation, such as the deformation of the components due to assembly forces or temperature loading during manufacturing. Flexible assemblies composed of slender parts or sheet metal components can deform substantially from their nominal geometric shape. Advanced Engineering Solutions has developed techniques that can perform tolerance analyses of flexible assemblies within the CAD environment. These techniques are described in the next chapter.

1) Technical Approach for tolerance analyses of flexible assemblies

a) Establish and validate a technique to add flexibility

The first step in this process is to establish and validate a technique to add flexibility to a parametric CAD model with slender components. A flexible component readily adapts to new, different, or changing requirements. It can be included in an assembly in various states. A spring, for example, can have various compression conditions in different places in an assembly. Values for flexibility can be defined before placement (predefined dimension), during placement (distance between two components) or after placement in the assembly.

Flexibility can be defined for any part or subassembly and can be used for every placement instance of the component. In order to make the component flexible in the assembly, set values or define the following items that will vary to allow the component to become flexible: dimensions, tolerances, parameters, and materials. Also flexible components have the ability to suppress or resume features and components (for subassemblies). Flexible components do not move and will lock the assembly's movement. In the Model Properties panel shown on Figure 1, one can declare a component as flexible. In order to select flexibility parameters you can go to the File -> Prepare -> Model properties menu. The flexibility can be declared under the tools group. One may select several sources of flexibility such as dimensions, geometric tolerances, parameters, features, references, surface finish, etc.

When a flexible component is placed in the assembly a message informs the user that the component has a predefined flexibility and prompts the user to select the faces that define the value of the flexibility parameter. Figure 2 shows the message window when a flexible component is to be placed in the assembly.

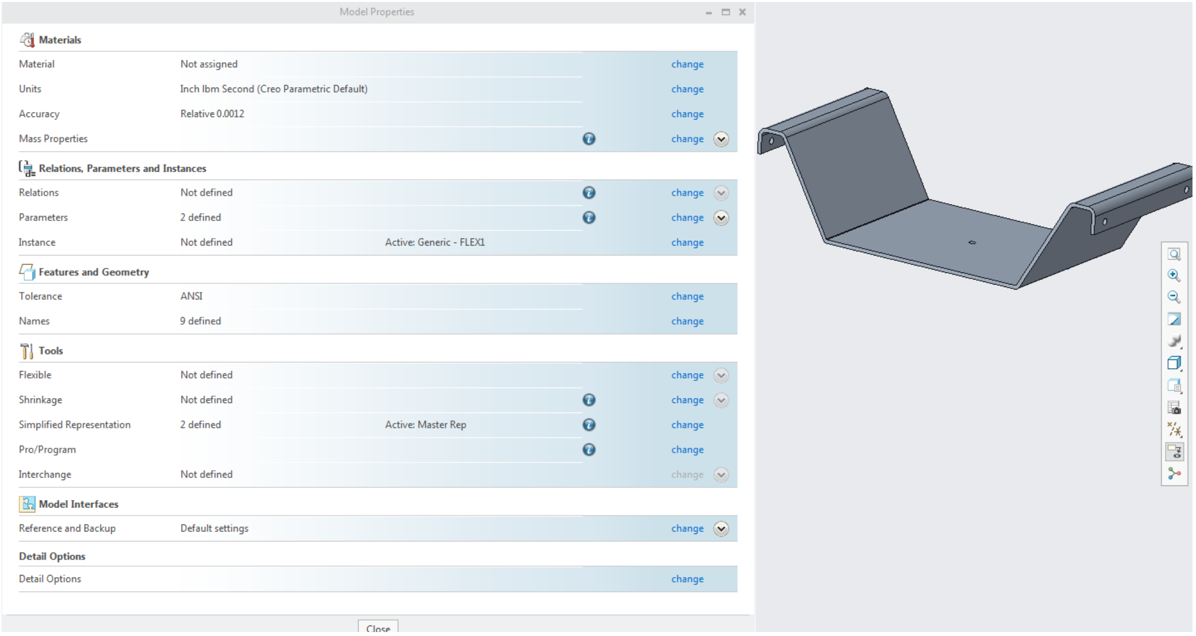

Figure 1 Model Properties Panel for Flexible Components

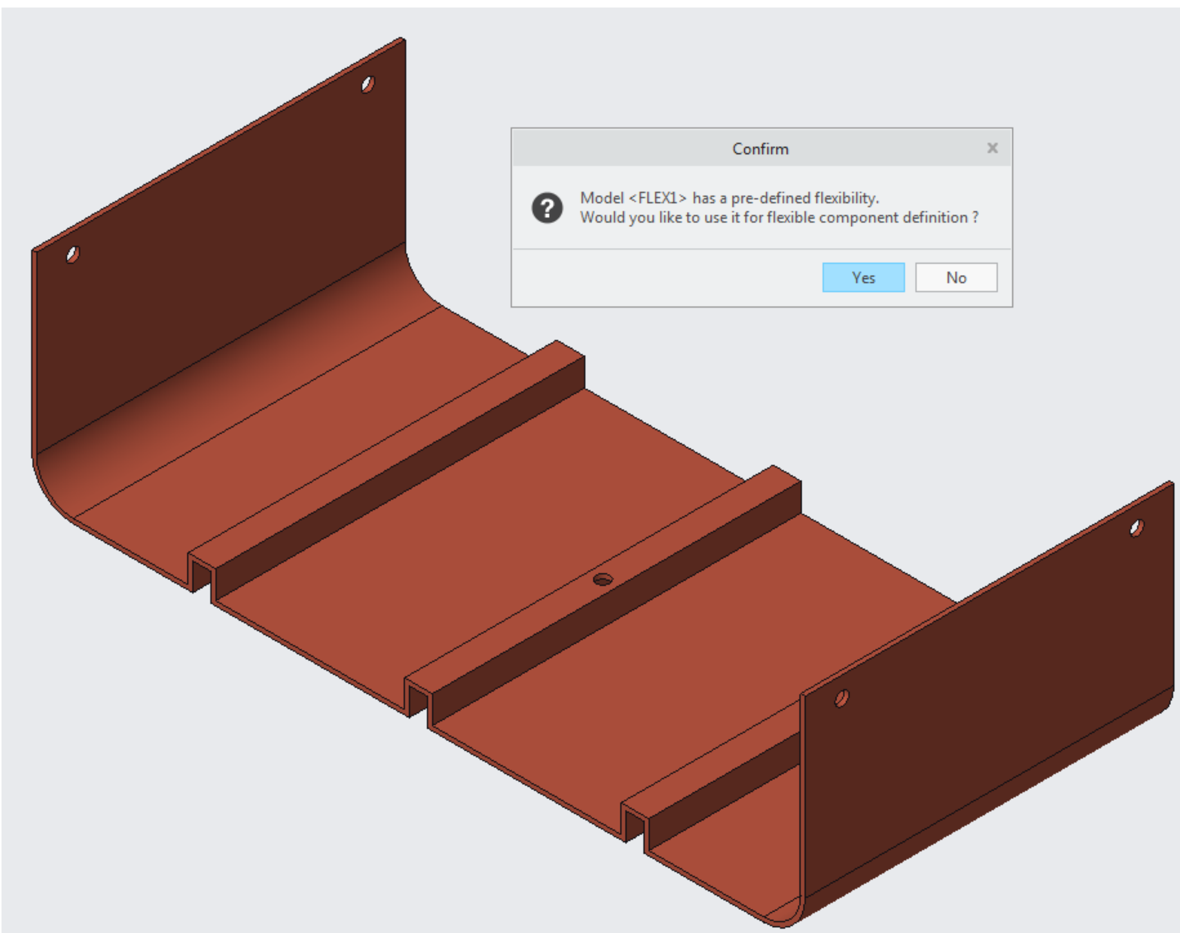

Figure 2 Placing a Flexible Component in the Assembly

The components will “bend” as a response to “Loading Parameters” entered in the CAD model. The CAD assembly should be easily integrated (or exported) to any commercially available tolerance analysis software such as Behavioral Modeling Extension (BMX), Tolerance Analysis Extension (TAE) or CETOL 6σ.

b) Use Sensitivity Analysis to Exercise the Model and visualize the Variation Impact

When the flexible component is assembled the model can be exercised to validate regeneration at the extreme conditions. In a process validation example two sheet metal components have been assembled. The height of the middle rib of the lower component, the angle of the slanted leg of the upper component and the flange length of the upper component exhibit significant variation. When the upper part is assembled and bolted to the lower component the part deforms. Figure 3 shows the assembly at the nominal position and Figure 4 at the extreme deformation. Exaggerating the variation confirms visually the correctness of the assembly constraints.

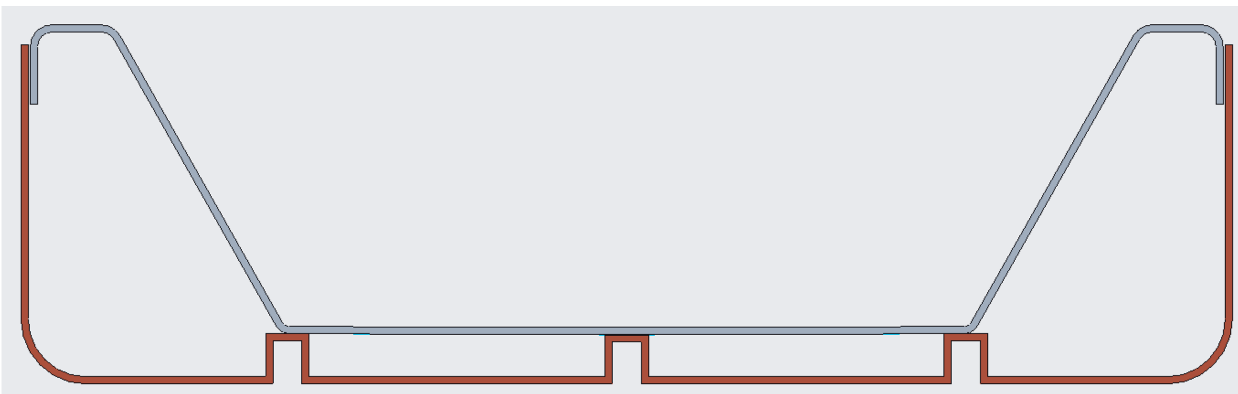

Figure 3 Sheet Metal Assembly at Nominal Condition

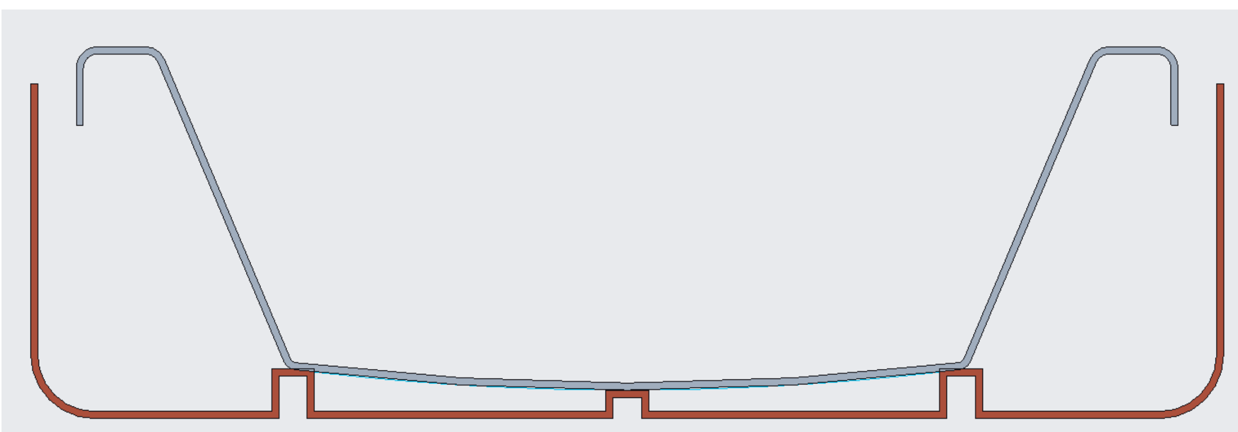

Figure 4 Sheet Metal Assembly at Extreme Deformation

A simulation feature can be generated that measures the eccentricity between the attachment holes on the flanges of the two components. A sensitivity analysis can be performed to assess the impact of the rib height on the holes' eccentricity. The sensitivity setup panel and the sensitivity plot are shown in Figure 5.

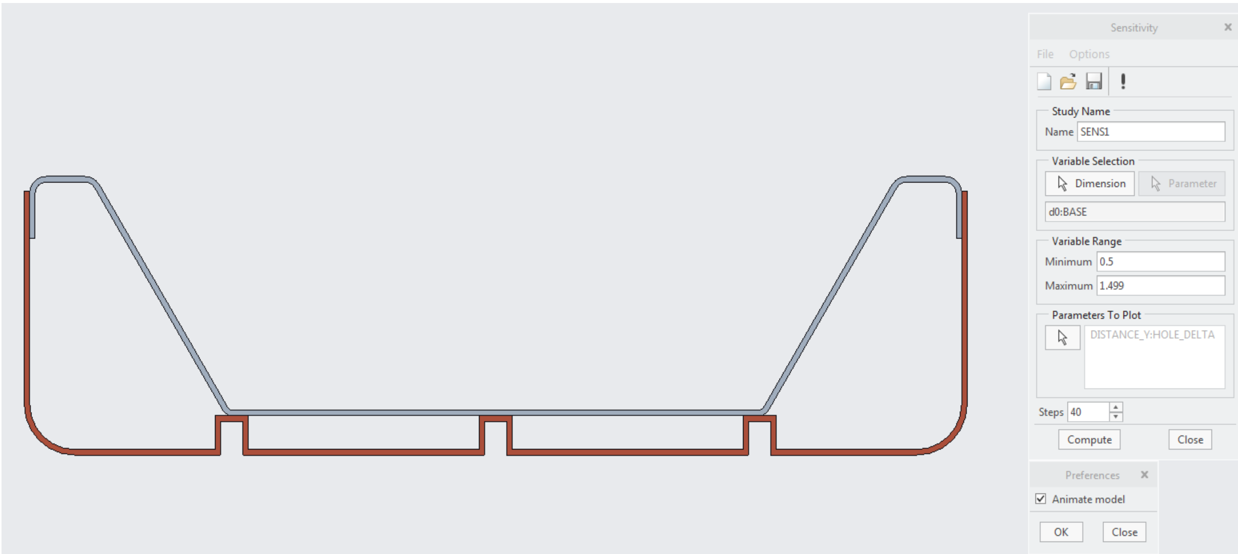

Figure 5 Sensitivity Analysis of the Rib's Height on the Holes' Eccentricity

c) Design of Experiments and Response Surface Approximation

Using the Multi-Objective Design Study capabilities of the CAD software the user can execute a Design of Experiments (DOE) on the "tolerance parameters" and generate a set of experiments (sampling space). Figure 6 shows the Multi-Objective Design Study set up. This is a scatter plot of all the sampling points of the rib height and the slanted part angle. For every DOE point the model is automatically regenerated and the holes' eccentricity is calculated. When all the set of "experiments" have been completed the Response Surface Approximation (RSA) can be generated. Several meta-models such as polynomial, Kriging or neural network for each one of the output variables (i.e. clearance A, clearance B, axis misalignment C, etc.) can be generated. One may evaluate the "goodness of the fit" of the RSA and determine if additional DOE points need to be generated and executed. Figure 7 shows the evaluation the "Goodness of the fit" at a specific value of angle and the flange height.

d) Statistical Tolerance Analyses

Since the RSA is available we can use Latin Hyper-Cube (LHC) Sampling technique and the tolerance parameters' stochastic distributions to generate a large (i.e. 10,000) set of DOE experiments. Figure 8 shows the statistical properties of the rib height variable. Figure 9 shows the statistical properties of the slope variable and Figure 10 shows the statistical properties of the flange height variable. All the LHC experiments can be executed using the RSA function and a large set of data can be generated for each output variable (performance metrics). The output data can be processed and the output distribution can be computed. Figure 11 shows the holes' eccentricity distribution. In addition if the lower and upper specification limits are specified the

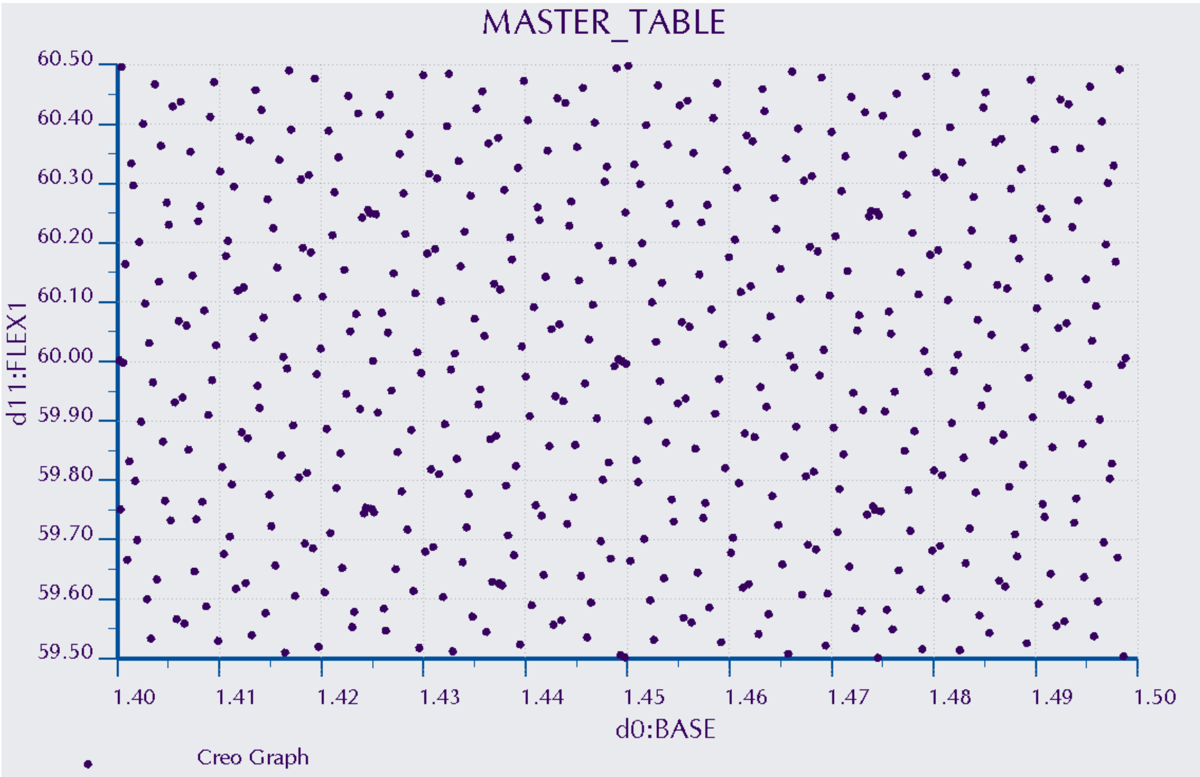

Figure 6 Multi-Objective Design Study set up

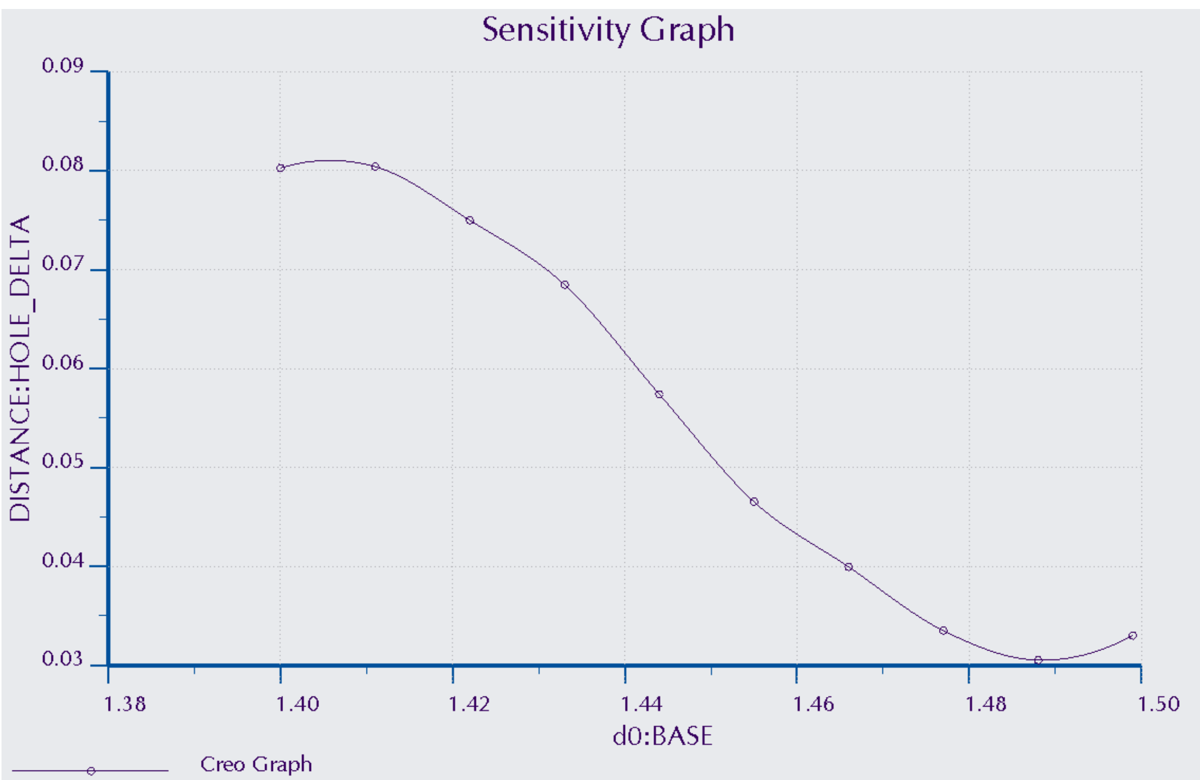

Figure 7 Evaluation the "Goodness of the fit" at a Specific Value of Angle and flange height

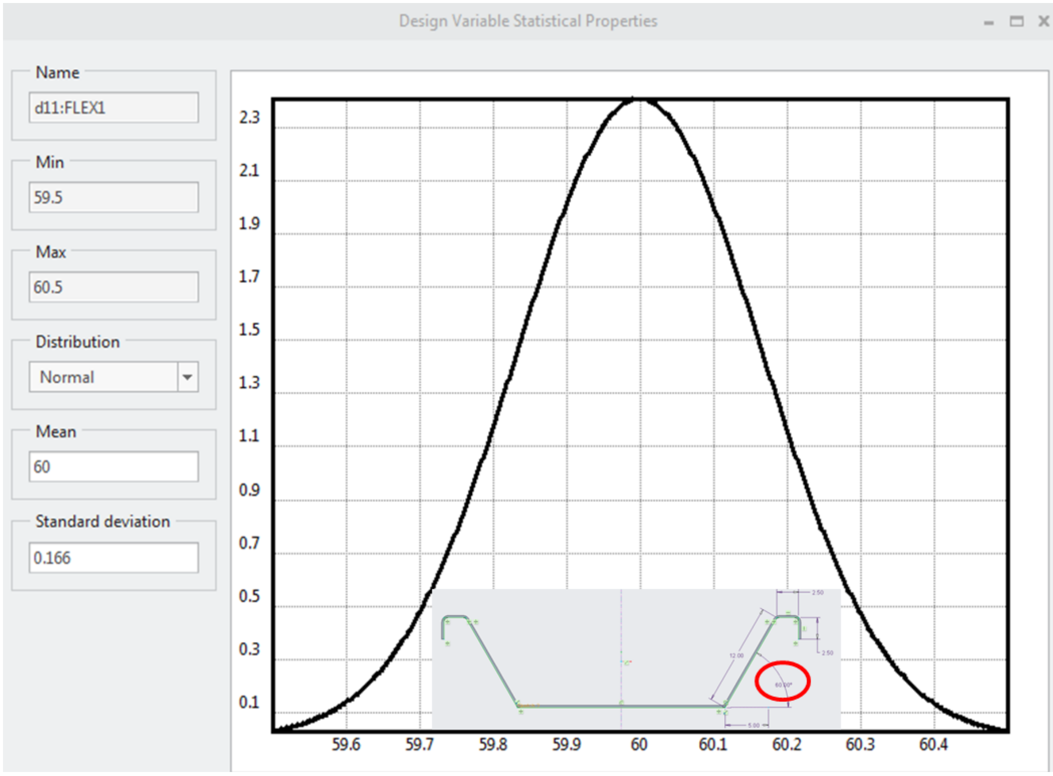

Figure 8 Statistical Properties of the Rib Height Variable

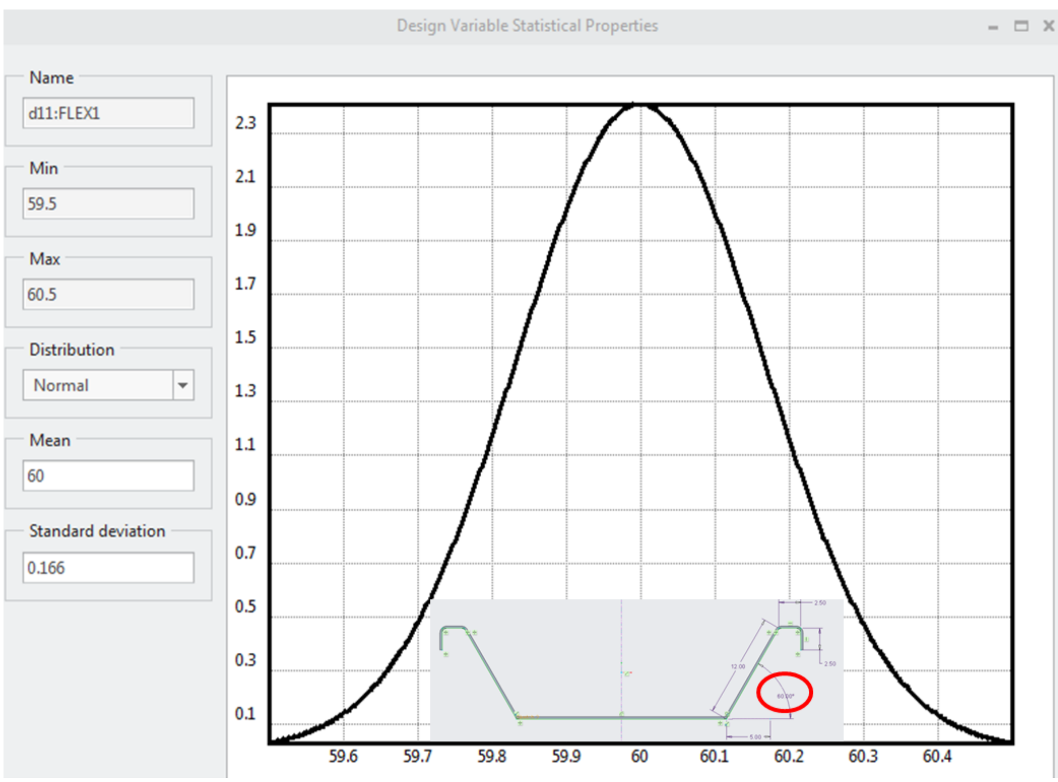

Figure 9 Statistical Properties of the Slope Variable

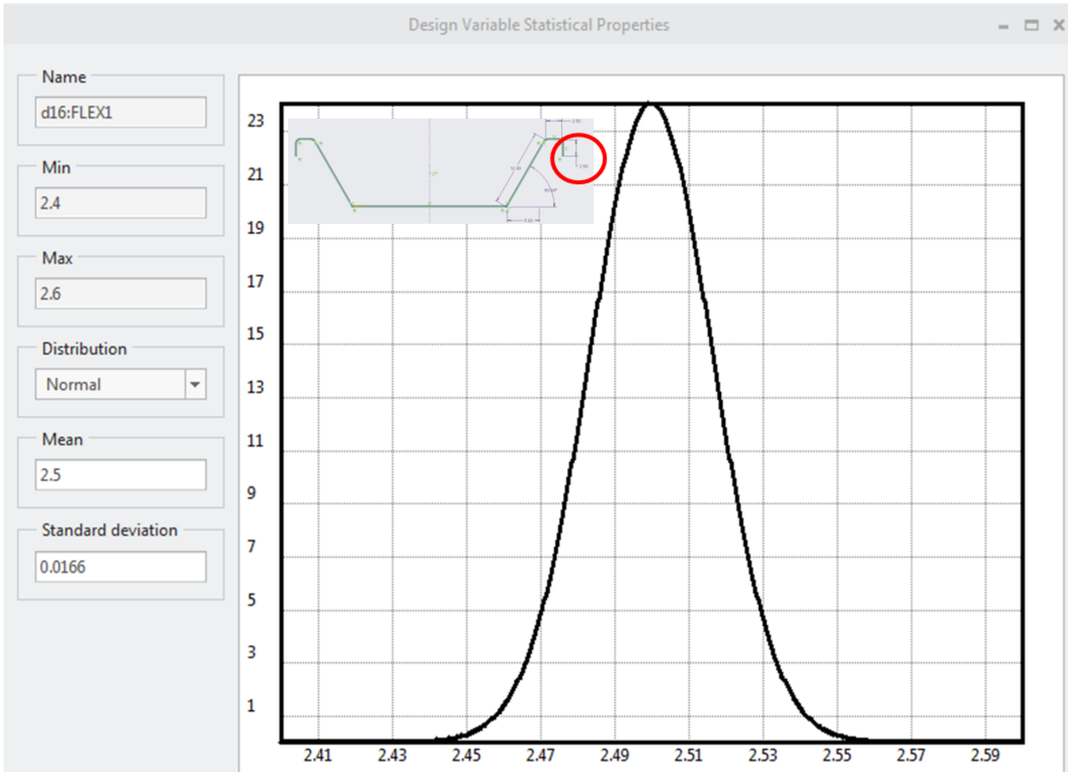

Figure 10 Statistical Properties of the Flange Height variable

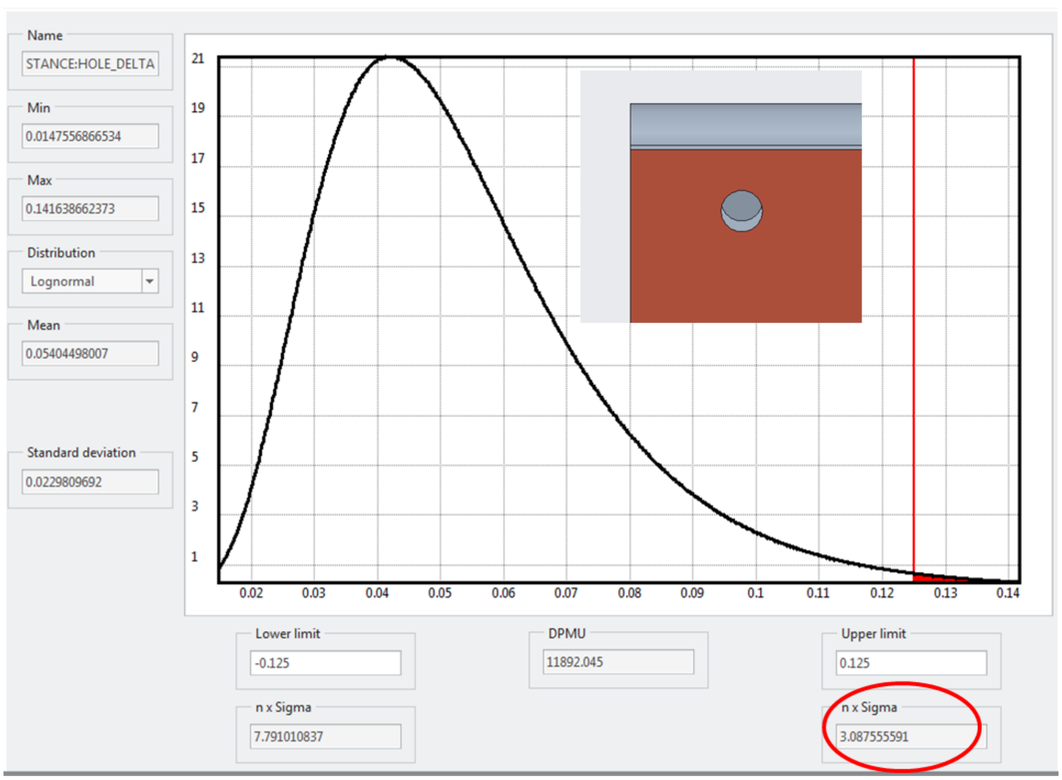

Figure 11 Holes' Eccentricity Distribution and Sigma Quality Level

Defected Parts per Million Units (DPMU) can be computed and displayed. The mean values and the standard deviations of all output variables can be computed and compared to the upper and lower specification limits. The distance of the mean to the closest specification limit in standard deviation units can be computed thus determining the Sigma Quality level. Figure 11 depicts all these results.

The deformation of flexible assemblies composed of slender parts or sheet metal components can be computed within the CAD systems (closed formed solution, forced displacement solution, Mathcad, etc.) and can be implemented using CAD flexible components. The described method can accomplish the tolerance analysis of flexible assemblies. Currently there is no access to semantic to GD&T information. The user needs to input the statistical input information of the variables with tolerance or variation. The parametric CAD models can be deformed easily with some planning. Non parametric CAD models can be deformed with spinal bends or deformed using direct modeling techniques (i.e. grouping morphing actions in ANSYS SpaceClaim). Complex structures require an interaction of FEA and design exploration software (Creo Simulate and BMX or ANSYS workbench and DesignXplorer) to perform statistical tolerance analysis.

e) Tolerance Analysis with Multiphysics Simulation

When the components or assemblies are *statically indeterminate structures* their deformation cannot be computed with simple equilibrium equations and therefore the previous technique cannot be used. In these cases the parametric CAD model needs to be linked to a computer Aided Engineering (CAE) model. If the CAD model is parametric the CAE model can understand the CAD parameters and rebuild automatically the parametric Finite Element Analysis (FEA) model. When the FEA model has the necessary material properties, loading and boundary conditions, the Multiphysics simulation can be performed. For example it can be a combination of a thermal model to find temperature distributions and a structural model to find the deformation due to the determined temperatures.
Figure 12 (a) and (b) shows the geometry of a simple example that is subjected to thermal loading. Electrical breakers have similar loading. If the geometry is not parametric and is available in a neutral file format (like STEP, PARASOLID, ACIS, IGES, etc.) it can be parameterized in a direct modeling system like ANSYS Space Claim, CREO flexible modeling etc. The surfaces can be selected and pulled in the desired direction. During the "pull" the surfaces can be grouped and the movement can be parameterized. Figure 13 shows the STEP file format Parametrization setup for the support distance. Figure 14 shows the STEP file format Parametrization setup for the slope angle.

The new parametrized CAD file can be dragged and dropped on the ANSYS steady state thermal analysis node. Figure 17 shows the workflow for this simulation and Figure 15 shows the temperature distribution of steady state thermal analysis. The results of the thermal analysis can be dragged and dropped on the structural analysis simulation node as shown in Figure 17. Figure 16 shows the displacement distribution due to the thermal expansion. The maximum deformation in the desired direction can be tagged and automatically becomes an output parameter of the simulation workflow. Using the Design Explorer of the ANSYS workbench we can easily perform a DOE study, generate the RSA, run a Probabilistic Analysis and compute the Sigma Quality Level of our metric (i.e. Clearence from ground components). Figure 17 shows the parameter set workflow. Figure 18 shows the Workflow for Statistical Tolerance Analysis of Flexible Assemblies.

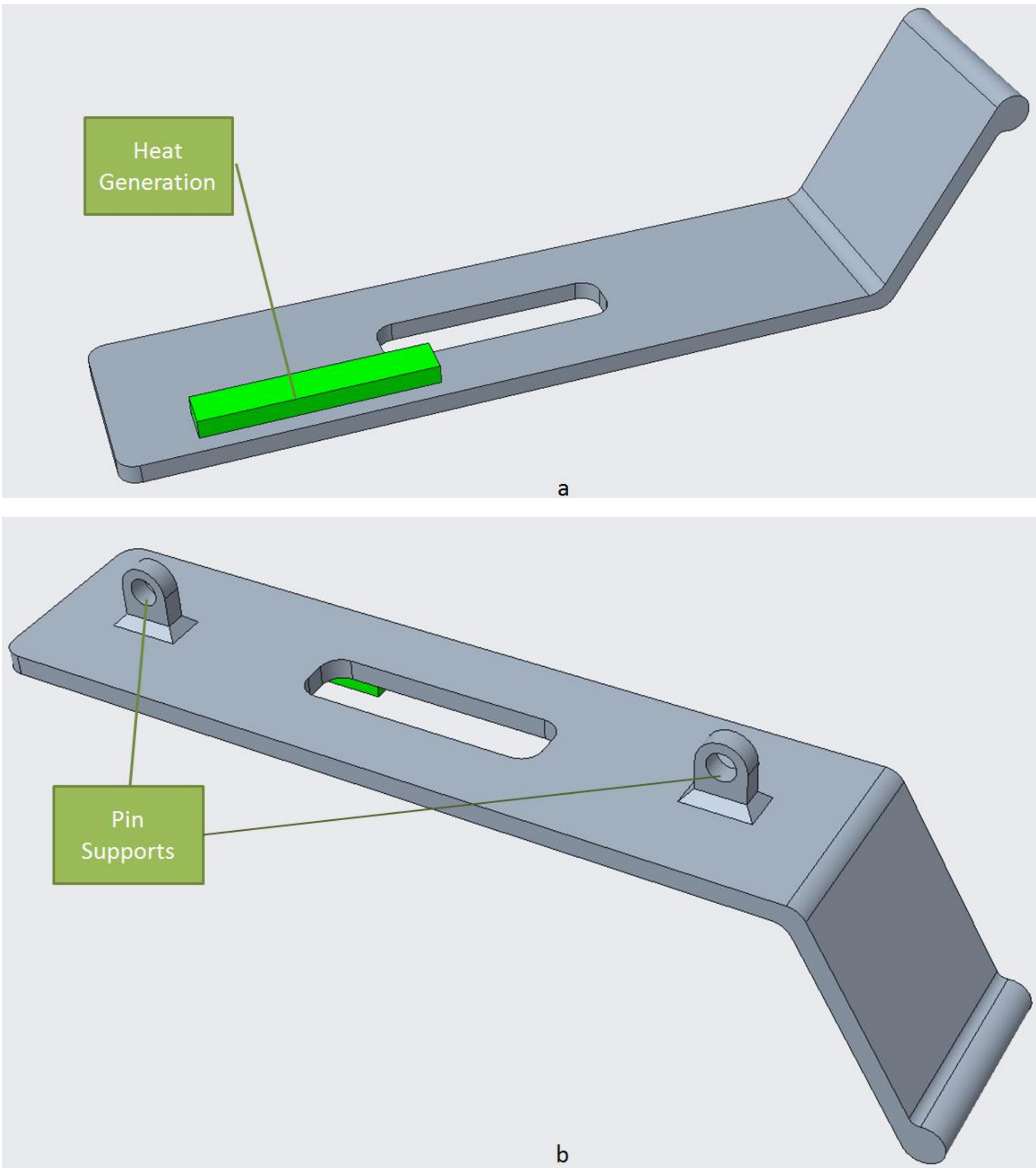

Figure 12 Geometry of a Simple Example that is subjected to Thermal Loading

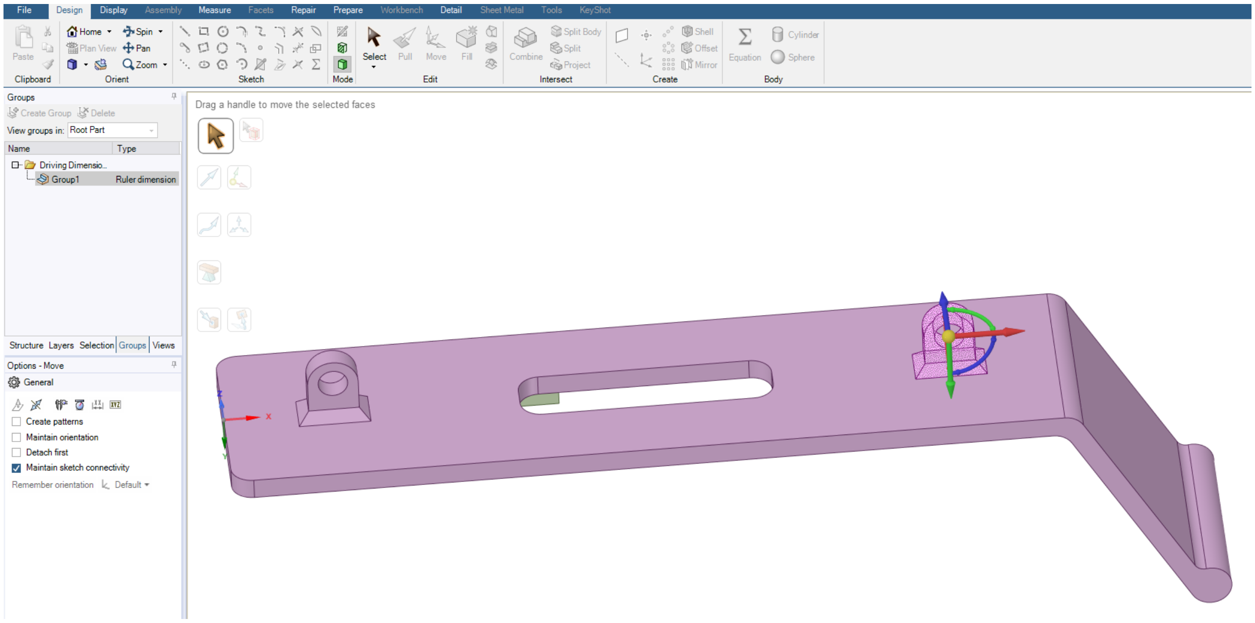

Figure 13 STEP file Parametrization setup for Support Distance

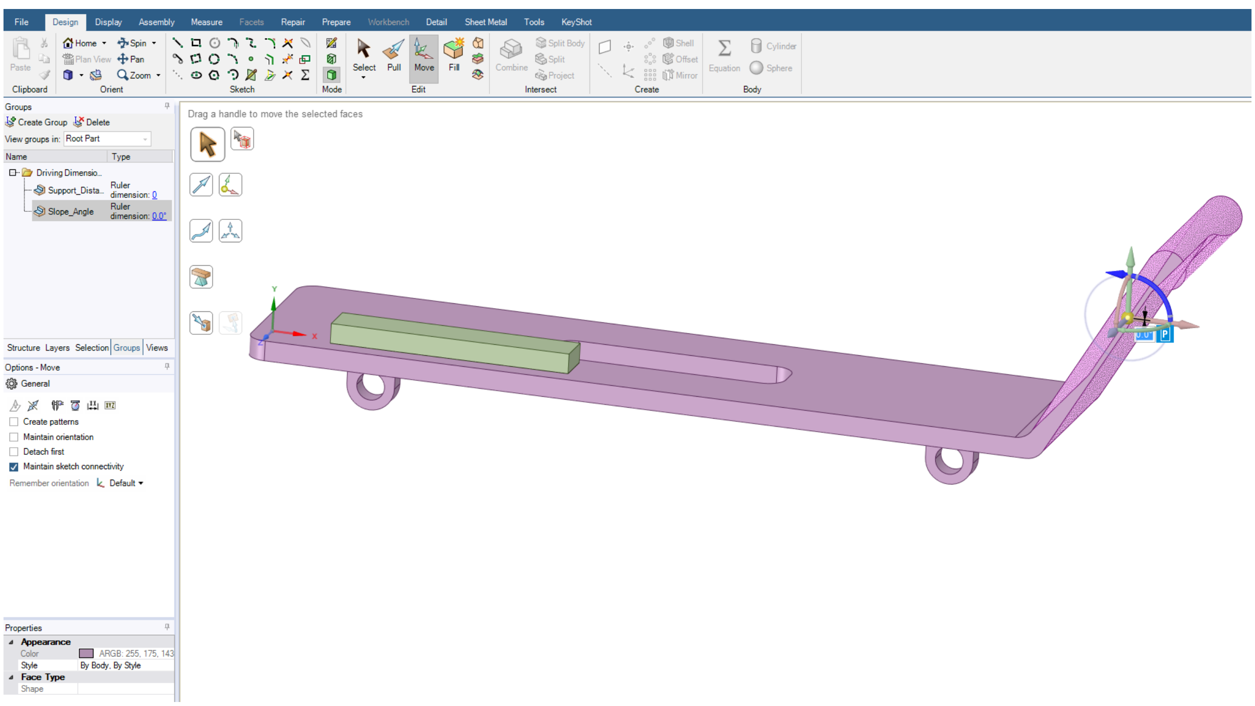

Figure 14 STEP file Parametrization setup for the Slope Angle

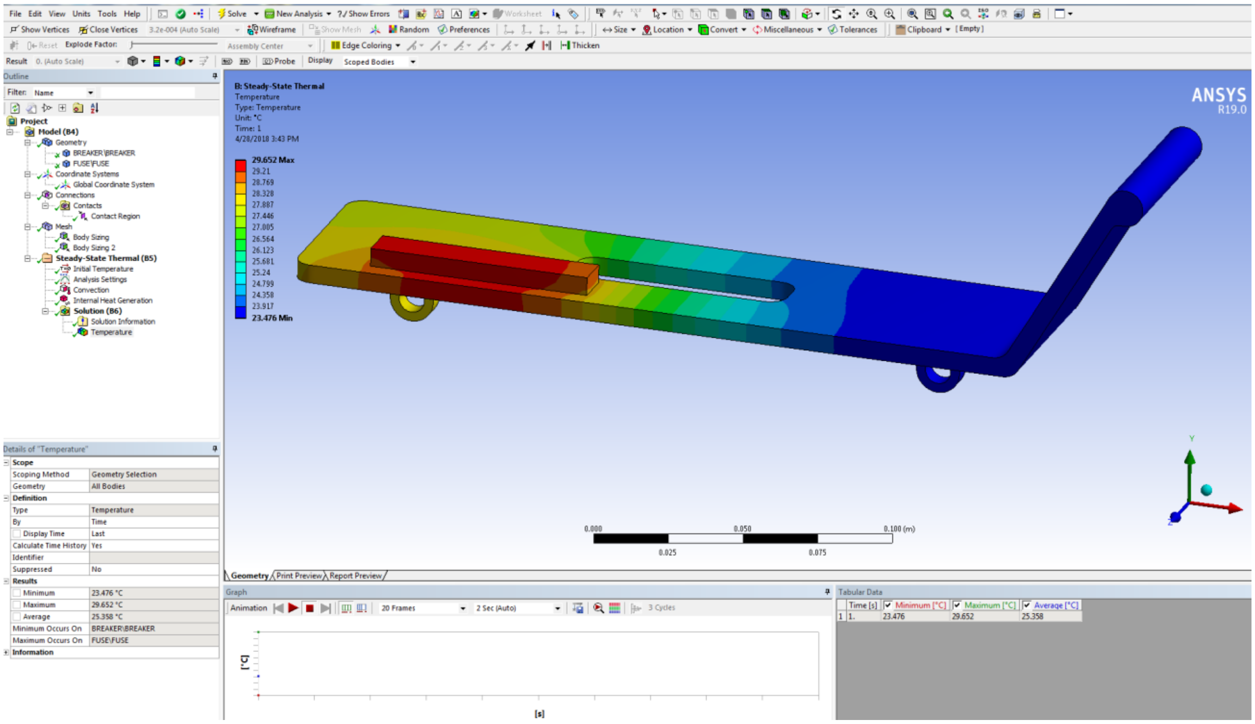

Figure 15 Temperature Distribution

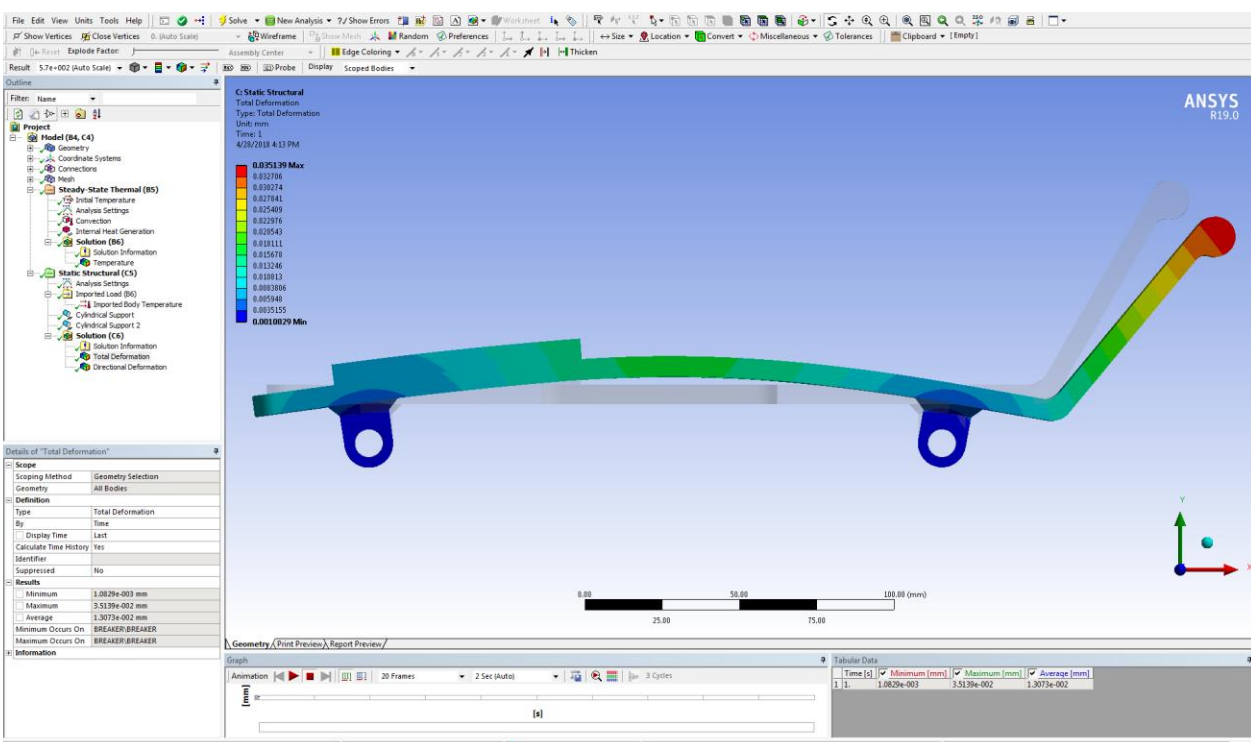

Figure 16 Amplified Deformed State due to Temperature Distribution

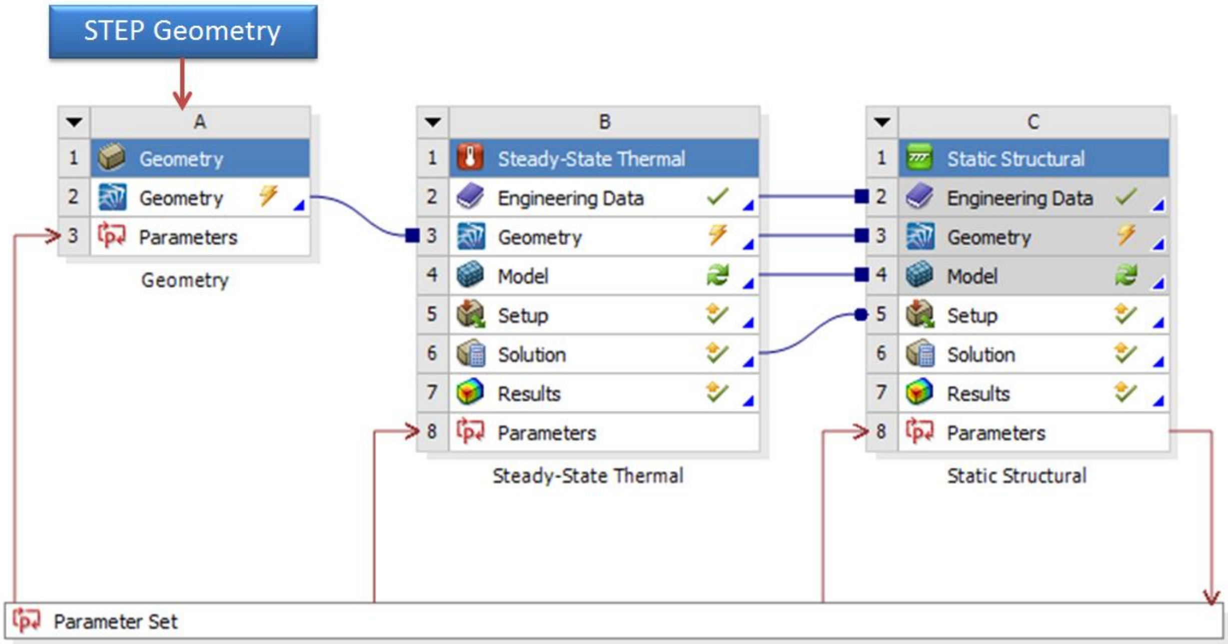

Figure 17 Workflow for Simulation, DOE, RSA, Probabilistic Analysis & Sigma Quality Level

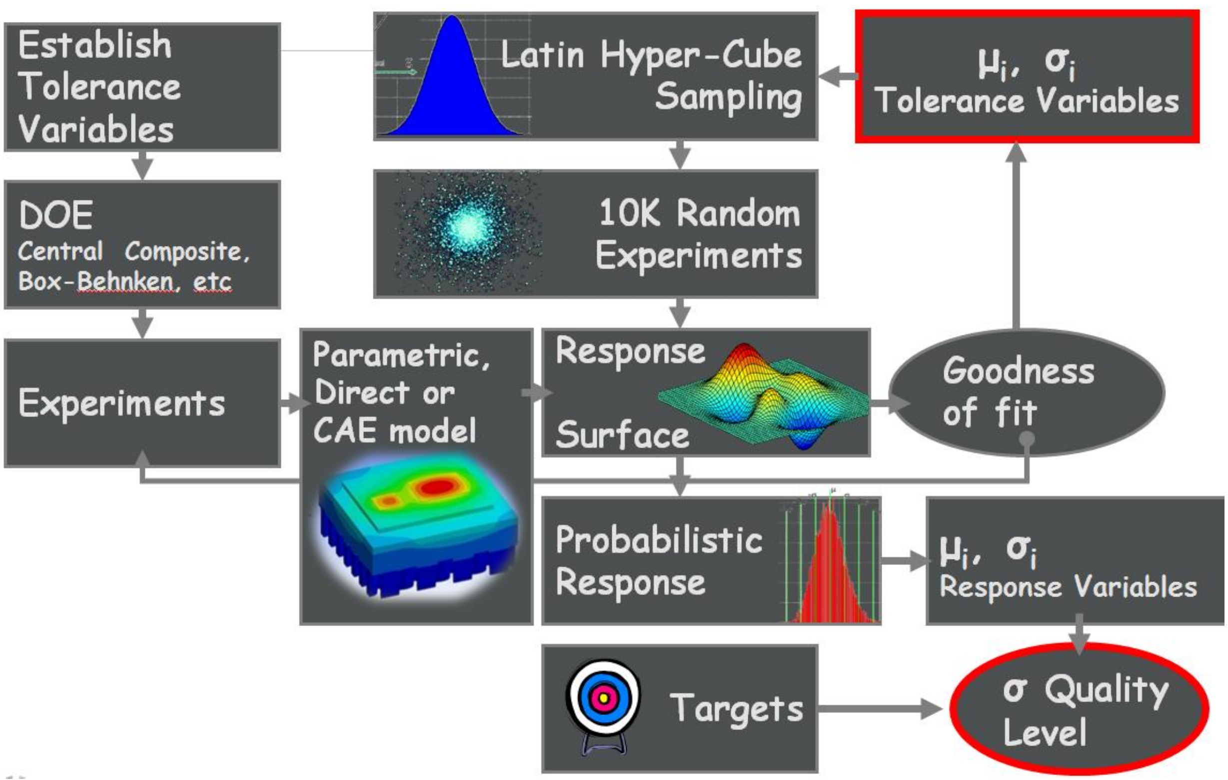

Figure 18 Workflow for Statistical Tolerance Analysis of Flexible Assemblies

III. KPI'S & METRICS

Section should minimally include the following:

Metric	Baseline	Goal	Results	Validation Method
Enter Metric	Enter Baseline	Enter Goal	Enter Results	Enter Validation Method
Ability to perform tolerance analysis of multi CAD or neural file assemblies	No tool is available	Develop a tool that can perform 1-D tolerance analysis of multi CAD or neural file assemblies	Developed an 1-Dimensional tolerance stack-up analysis program	Live demonstration of validation models
Ability to perform tolerance analysis of flexible assemblies within the CAD environment	No tool is available to perform the tolerance analysis of flexible assemblies within the CAD environment	Develop the process to perform the tolerance analysis of flexible assemblies within the CAD environment and the process to integrate with Multi-Physics CAE tools	Developed and demonstrated the process to perform the tolerance analysis of flexible assemblies within the CAD environment and the process to integrate with Multi-Physics CAE tools	Live demonstration of validation models and final report with descriptions

IV. TECHNOLOGY OUTCOMES

A 1-Dimensional tolerance stack-up analysis program EZTol has been developed and is available to the DMDII members at no cost for a year.

A process to perform the tolerance analysis of flexible assemblies within the CAD environment and the process to integrate with Multi-Physics CAE tools has been developed and demonstrated. These processes are available to all DMDII members.

III. ACCESSING THE TECHNOLOGY

a. Background Intellectual Property

The process to perform the tolerance analysis of flexible assemblies within the CAD environment and the process to integrate with Multi-Physics CAE tools is available to all DMDII members and the design and manufacturing community at large.

b. Technical and Systems Requirements

A windows work station with any major parametric CAD system, a direct modeling CAD and ANSYS workbench.

VI. INDUSTRY IMPACT & POTENTIAL

a. Impact to the specific market the project was addressing and size of that market

Having an easy-to-use process that works directly within the CAD environment enables immediate feedback to the designer. The ability to simulate flexible components improves the quality of assemblies that deform due to loading, contact forces, welding distortion, temperature variations, etc.

b. How could this technology be used in other industries

This process can be used in any Design for Six Sigma (DFSS) effort. If during the design process, there is uncertainty in input parameters such as dimensions, material properties, loading conditions then this process can be used for robustness assessment of the design and therefore a quality improvement of the design.

c. Next step based on other use potential

DMDII can sponsor a Design for Six Sigma course for the members. The process of this research effort will enable the participants to generate robust designs at the presence of controlled and uncontrolled variations.

VII. TECH TRANSITION PLAN & COMMERCIALIZATION

The EzTol software is TRL level 10 and is commercially available. Several YouTube videos are available with software demonstrations.

The Tolerance Analysis Techniques for flexible assemblies developed under this research effort are TRL level 9. Manufacturers that can implement these techniques will reduce the amounts of money that they spend on product quality issues such as parts not fitting together properly, scrap, and rework.

VIII. WORKFORCE DEVELOPMENT

The step-by-step workflows for performing Tolerance Analysis of flexible assemblies are available to DMDII members.

The AES team participated at the ASSESS 2017 Congress (Analysis, Simulation & Systems Engineering Software Strategies). Dr. Vlahinos was a Technology Briefing Leader and presented on "Understanding the Role of Product Performance Information (PPI) on Enabling Enhanced MBD" topic. Results of this project were presented and the DMDII support was acknowledged. Bolger Center in Potomac, MD, November 1-3, 2017

The AES team participated at the 33rd International CAE conference focused on "Simulation: The Soul of Industry 4.0." Dr. Vlahinos was a session chair and he presented a paper entitled "Tolerance Analysis

Techniques for Flexible Components." Results of this project were presented and the DMDII support was acknowledged. Vicenza, Italy, Nov 6-7, 2017

IX. CONCLUSIONS/RECOMMENDATIONS

A 1-Dimensional tolerance stack-up analysis program for multi CAD assemblies has been developed and I is commercially available. DMDII members can have free access to this software tool for a year.
A process to perform the tolerance analysis of flexible assemblies within the CAD environment has been developed and demonstrated. The process to can integrate CAD geometry with Multi-Physics CAE tools to perform tolerance analysis of assemblies with thermal and structural loadings.

X. LESSONS LEARNED

Section should minimally include the following:

a. Problems Encountered

The large companies are slow to respond in providing typical industry problems in the area of tolerance analysis on assemblies with flexible components.

In order to protect their IP, there is also some hesitance of companies to provide CAD data of their products.

b. Plan/Scope of Work/Proposal Claim Deviations

The team built a CAD assembly based on discussions, sketches or photos of publicly available data (publications, products, etc.) to generate the validation problems

c. Risks Realized

The major risk of implementation of this research effort is the lack of uncertainty quantification. Typically the designers know the mean values of dimensions, material properties, loading conditions, temperatures but they don't have access to the variation of these quantities (i.e. standard deviation).

XI. DEFINITIONS

BMX Behavioral Modeling Extension in CREO Parametric

CAD Computer Aided Design

CAE Computer Aided Engineering

CpK Process Capability Index

DOE Design of Experiments

DPMO Defected Parts per Million Opportunities

GD&T Geometric Dimension and Tolerancing

FEA Finite Element Analysis

IP Intellectual Property

PMI Product Manufacturing Information

RSA Response Surface Approximation

RSS Root Sum Squared

STEP STandard for Exchange of Product model data